Photonics and Nanostructures – Fundamentals and Applications 25 (2017) 52–57

Contents lists available at ScienceDirect

Photonics and Nanostructures – Fundamentals and Applications

journal homepage: www.elsevier.com/locate/photonics

Numerical studies on a plasmonic temperature nanosensor based on a metal-insulator-metal ring resonator structure for optical integrated circuit applications

Md. Jubayer Al-mahmod, Rakib Hyder, Md Zahurul Islam*

Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka, 1205, Bangladesh

ARTICLE INFO

Article history:
Received 4 February 2017
Received in revised form 6 May 2017
Accepted 10 May 2017
Available online 17 May 2017

Keywords:
Surface plasmon resonance sensor
Metal-insulator-metal waveguide
Plasmonic temperaturesensor
Finite-difference time-domain method
Optical integrated circuit

ABSTRACT

A nanosensor, based on a metal-insulator-metal (MIM) plasmonic ring resonator, is proposed for potential on-chip temperature sensing and its performance is evaluated numerically. The sensor components can be fabricated by using planar processes on a silicon substrate, making its manufacturing compatible to planar electronic fabrication technology. The sensor, constructed using silver as the metal rings and a thermo-optic liquid ethanol film between the metal layers, is capable of sensing temperature with outstanding optical sensitivity, as high as $-0.53\,\mathrm{nm}/^{\circ}\mathrm{C}$. The resonance wavelength is found to be highly sensitive to the refractive index of the liquid dielectric film. The resonance peak can be tuned according to the requirement of intended application by changing the radii of the ring resonator geometries in the design phase. The compact size, planar and silicon-based design, and very high resolutions- these characteristics are expected to make this sensor technology a preferred choice for lab-on-a-chip applications, as compared to other contemporary sensors.

1. Introduction

An optical temperature sensor exploits the property of temperature-dependence of refractive index of an optical material to measure the ambient or local temperature. Many different exceptionally-promising research directions for advanced optical temperature sensing technologies have already been reported in the literature on account of the many attractive potential advantages of optical sensing, such as very high sensitivity, large measuring ranges, stability, and immunity to environmental disturbances. In recent investigations of optical temperature sensors, many different optical phenomena have been exploited, for instance, Bragg-grating-based sensors [1], interferometric sensors [2–5] and plasmonic sensors [6–8]. Grating-based sensors are very complex to fabricate. Although the modal interferometer-based sensors are better from the fabrication point of view, their precision is not robust as their interference pattern may drift in real time [9]. Most importantly, since the working principles of these sensors are based on optical phenomena, the minimum feature size for chip-scale fabrication could be at best on the order of the wavelength of the optical signal. Consequently, true nanosensors, for on-chip or local temperature sensing applications, cannot be implemented by using these aforementioned technologies. The plasmonic sensor technology is promising because it can alleviate the low precision and sensitivity problems. Also the plasmonics phenomenon, in principle, can manifest itself in nano-scale regime and thus is capable of driving the sensor technology into further miniaturization. As such, different plasmonic temperature sensors have already been proposed and demonstrated due to phenomenal improvement in nano-fabrication and nano-characterization technologies. A temperature sensor based on photonic crystal surface plasmon polariton (SPP) waveguide has been proposed and a sensitivity of $-0.07\,\mathrm{nm}/^{\circ}\mathrm{C}$ is reported [9]. But still the temperature sensitivity is low and the sensor size is quite large so that they are not yet up to the requirements for lab-on-a-chip or other on-chip applications. Recently, some SPP-based sensors have been realized and fabricated for sub-wavelength electromagnetic wave confinement, thus overcoming the diffraction limit to yield high density photonic integrated circuits and sensors [10,11].

It is well known that plasmonic metal-insulator-metal (MIM) structures have strong confinement property along with long propagation ranges [12]. When it is desired to increase the sensitivity of a sensing device, it is indispensable not only to increase the confinement of the electric field, but also to maximize the interaction length of the field with the sensing substance. In geometrically compact devices, one potential way of increasing the

* Corresponding author.
E-mail address: mdzahurulislam@eee.buet.ac.bd (M.Z. Islam).

http://dx.doi.org/10.1016/j.photonics.2017.05.001
1569-4410/

interaction length can be to incorporate hybrid cavities to facilitate re-circulation of optical and plasmonic resonance waves. Therefore, we can hypothesize that an MIM ring resonator structure in a sensor configuration, which acts as both optical and plasmonic hybrid cavities, will greatly increase the sensitivity of the resulting sensing device.

There are many reports of different types of resonator-based temperature sensors in literature. One such type is whispering gallery mode (WGM) resonator-based sensors. They were found to be highly sensitive to the ambient refractive index [13,14]. A WGM resonator based sensor is proposed and demonstrated with a sensitivity of 0.377 nm/°C [15]. For microfiber knot resonator, a sensitivity of 0.28 nm/°C and a temperature resolution of 0.5 °C are experimentally demonstrated [16]. However, the detection limit suffers because of technical noise sources. Therefore, current research on WGM sensors is focused on mitigating this effect by enhancing the light-matter interaction [15]. Hence plasmonic nanosensors can play a key role in reducing limit of detection and footprint, compared to the microcavity-based sensors.

In quest of high density integration and compactness, we propose an MIM ring resonator based temperature sensor in this paper. Moreover, we have incorporated silicon as substrate for the device to make it compatible with the standard planner electronic fabrication processes [17]. The spectral response of the proposed nanosensor is investigated numerically and analytically. The sensing performance of the device is evaluated and the device is found to be much smaller and much more sensitive than the contemporary reported sensors in [18–20].

2. Sensor configuration and method of analysis

The sensor configuration is shown in Fig. 1. It consists of an MIM ring cavity/resonator and two silicon waveguides (length 180 nm and width 260 nm) to guide EM waves to and from the ring. Strong confinement of SPP waves around the interfaces and long propagation range in the NIR region of the electromagnetic spectrum have made MIM waveguide structures particularly attractive for sensing applications. The generalized theory depicts that coupled modes between the two interfaces are generated if the spacing between them is made less than the decay length of interface modes [12]. This coupling of modes contributes to the strong confinement of SPP wave in the MIM structure. As mentioned earlier, strong confinement and long interaction length both contribute to the enhancement of sensitivity of a sensing device. In the proposed structure, MIM waveguide formed a ring resonator so that the interaction length increases due to the repetitive re-circulation of the wave thereby greatly increasing the sensitivity of the resulting sensor device. Moreover, This ring structure reduces the footprint of the device.

The refractive indices of the materials constituting the ring can be used to manipulate the electromagnetic properties of the SPP [12]. If we assume that changes in the real and imaginary parts of permittivity of the metal (silver) layers with change in temperature are negligible, any variation in the refractive index of the dielectric portion of the ring will manifest itself as a change in the electromagnetic properties (e.g. shift of resonance peak) of the generated SPPs. Therefore, we chose a dielectric material for the MIM ring that has a high refractive index sensitivity to the operating temperature. A liquid dielectric with high refractive index temperature coefficient is a preferable choice for this type of applications. Our assumption of negligible dependence of real and imaginary part of the permittivity of silver on temperature is valid for low energy excitations, from visible to longer wavelengths electromagnetic waves, and at least for temperature range of 0 K to 600 K [21]. An inspection of Fig. 7 in Reference [21] clearly validates this assumption. In this work, we have chosen our excitations to be in the NIR spectrum to keep this assumption applicable to our system and also to avoid losses due to inter-band transition.

Silver is considered as a noble metal due to its low absorption property. The optical constant, permittivity, of silver can be described by the well-known Drude mode as follows:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{{\omega_p}^2}{{\omega_p}^2 + i\omega\gamma} \tag{1}$$

where ε_∞ = 3.7, ω_p = 9.1 eV and γ = 18 meV for silver [22].

IR wave is launched to the ring through the waveguide I and the transmitted wave is monitored in the waveguide II (i.e. in monitor M-2). The resonance wavelength of the MIM ring resonator can be calculated using the following transcendental equation [23]:

$$\frac{J'_n(kr_o)}{J'_n(kr_i)} = \frac{N'_n(kr_o)}{N'_n(kr_i)} \tag{2}$$

where, J_n is an n-th order Bessel function of the first kind, N_n is an n-th order Bessel function of the second kind. $J¢_n$ and $N¢_n$ are the derivatives of the Bessel function to the argument (kr). r_i is the inner and r_o represents the outer radius of the ring, and $k = \omega\sqrt{\varepsilon_0\varepsilon_r\mu_0}$. μ_0 is the air permeability and frequency-dependent effective permittivity, $\varepsilon_r = \eta_{eff}^2/\mu_0$. It is immediately perceived from the Eq. (2) that the radii of the ring and the refractive index of the dielectric have an influence on the resonance wavelength, hence can be used in sensing. Both of the effects are investigated in this paper.

At the resonance wavelength, the cavity mode is excited and allows the EM wave transmission to the waveguide II. On the other hand, far from the resonance wavelength, the incident mode is reflected leaving, meager amount of power left in the waveguide II. Also inevitable ohmic loss in the metal precludes the normalized transmittance to reach unity. The resonant wavelength of an MIM ring resonator can be approximated as [23]:

$$\lambda_r = \frac{mc}{rn_{eff}} \tag{3}$$

Here, m is a positive integer indicating the resonant mode number, c is the free-space speed of light and $r = (r_i + r_o)/2$ is the average radius of the ring. The dispersion relation for such an MIM structure is [24]:

$$tanh\left(\frac{\omega}{2}\sqrt{\beta^2 - \varepsilon_d k_0}\right) = \frac{-\varepsilon_d\sqrt{\beta^2 - \varepsilon_d k_0}}{\varepsilon_m\sqrt{\beta^2 - \varepsilon_m k_0}} \tag{4}$$

where, b is the propagation constant of the generated SPPs. The proposed nanosensor is composed of an average radius r = 200 nm and with a spacing of the dielectric w = 300 nm. Eq. (4) provides an effective refractive index $\eta_{eff} = Re\left(\beta/k_0\right)$, where $k_0 = 2\pi/\lambda_0$ is the free-space wave-vector.

Fig. 2 is a simple representation of the sensing system that comprises of a broadband EM source and an optical spectrum analyzer (OSA) that detects the resonance information.

The refractive index of the liquid dielectric layer can be related to its temperature using the following equation [25]:

$$\eta = \eta_0 + \frac{d\eta}{dT}(T - T_0) \tag{5}$$

where T_0 is reference temperature and $d\eta/dT$ is the temperature coefficient of refractive index of the liquid. Therefore, larger $d\eta/dT$ represents the better refractive index sensitivity of the liquid to the temperature. Because of this, a liquid with high refractive index temperature coefficient is required to fill the space between the rings to achieve high sensitivity. Finally sealing the liquid dielectric layer properly will prevent other ambient perturbations. Ethanol is an excellent choice for the dielectric layer which has been reported to have a very high temperature coefficient of refractive index.